Developing Extinction Criteria for Fires

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Overview

Introduction

- Poorly Ventilated Fires
- Extinction Problem Formulation

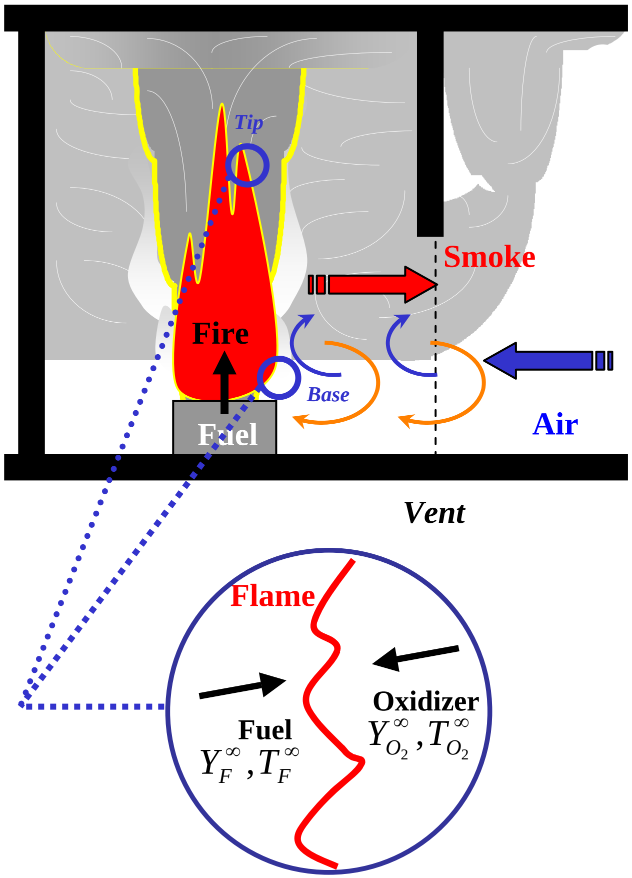
Kinematic Scale Analysis for Fire

Extinction Analysis for Fire

- Experiments
- OPPDIF Simulations
- Asymptotic Theory
- Critical Damköhler Number
- Critical Scalar Dissipation Rate Model

Summary and Future Work

Introduction: Poorly Ventilated Fires



$$Y_{O_2}^\infty \le Y_{O_2,a}$$
$$T_{O_2}^\infty \ge T_a$$

Extinction Effects

- Extinction places raw fuel in smoke increasing its toxicity and contributing to CO production.
- Local or global vitiation (typical of compartment fires) makes flame vulnerable to extinction.

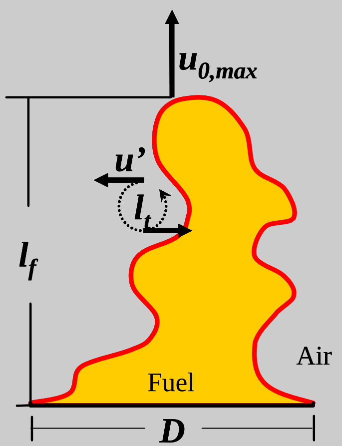
Extinction Criteria

- In fire, this vulnerability typically expressed in terms of a global O_2 concentration.
- Recognizing that extinction is a local flame phenomenon (Simmons and Wolfhard, 1957) and later (Ishizuka and Tsuji, 1981) established a criterion where extinction occurs when $Y_{O_2}^\infty < 0.16$ at 300K for weakly strained methane flames.

Introduction: Extinction Problem Formulation

- Strictly, extinction criteria must include composition, temperature, and **flow effects**.
- It is necessary to assess the relative importance of these effects and apply them to fire simulation tools.

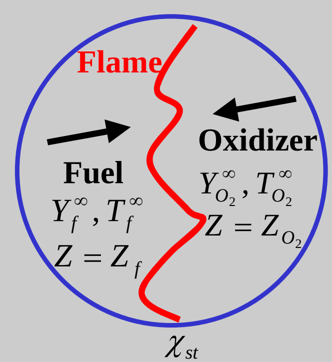
Scale Analysis



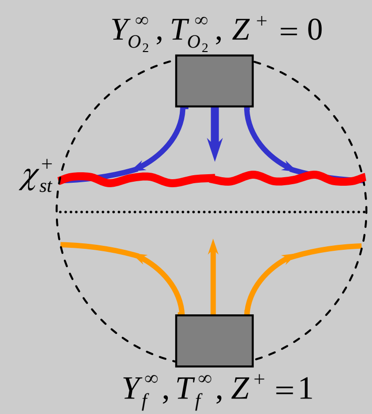
Determine flow conditions in the flame zone for accidental fires.

Extinction Analysis

Local Flame



Flamelet



Determine convenient extinction criteria at these flow conditions.

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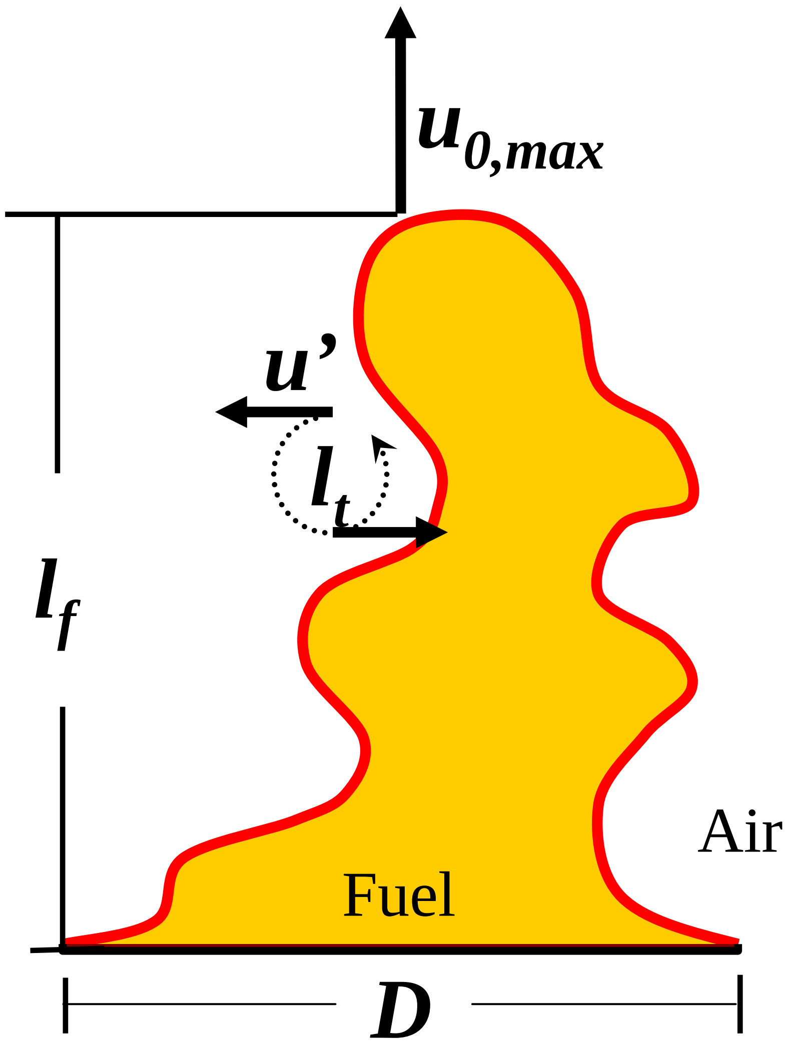
Kinematic Scales in Fires



- Use well known and experimentally validated scaling laws to predict large scale motions.
- Use Kolmogorov scaling arguments to predict small scale motions (local strain rate) from the large scale motions.
- Analytic solutions from asymptotic analysis predict a characteristic scalar dissipation rate.

Kinematic Scales in Fires

Fire Scale	Integral Scale	Kolmogorov Scale
D	$l_t = 0.5D$	$\eta_k = l_t \, \mathrm{Re}_t^{-3/4}$
$\dot{Q} = \Delta h_c \dfrac{\pi D^2}{4} \dot{m}''_\infty (1 - e^{-kBD})$	$u' = 0.3 u_{0,\max}$	$V_k = u' \, \mathrm{Re}_t^{-1/4}$
$u_{0,\max} = 0.54 (\Delta T_0 \dfrac{\dot{Q}}{1000})^{1/5}$	$\mathrm{Re}_t = \dfrac{u' l_t}{\nu}$	$a_t = \dfrac{V_k}{\eta_k}$

$$\chi_{st} = \varphi(a_t / \pi) \exp\left\{ -2 \left[\mathrm{erfc}^{-1}(2 Z_{st}) \right]^2 \right\}$$

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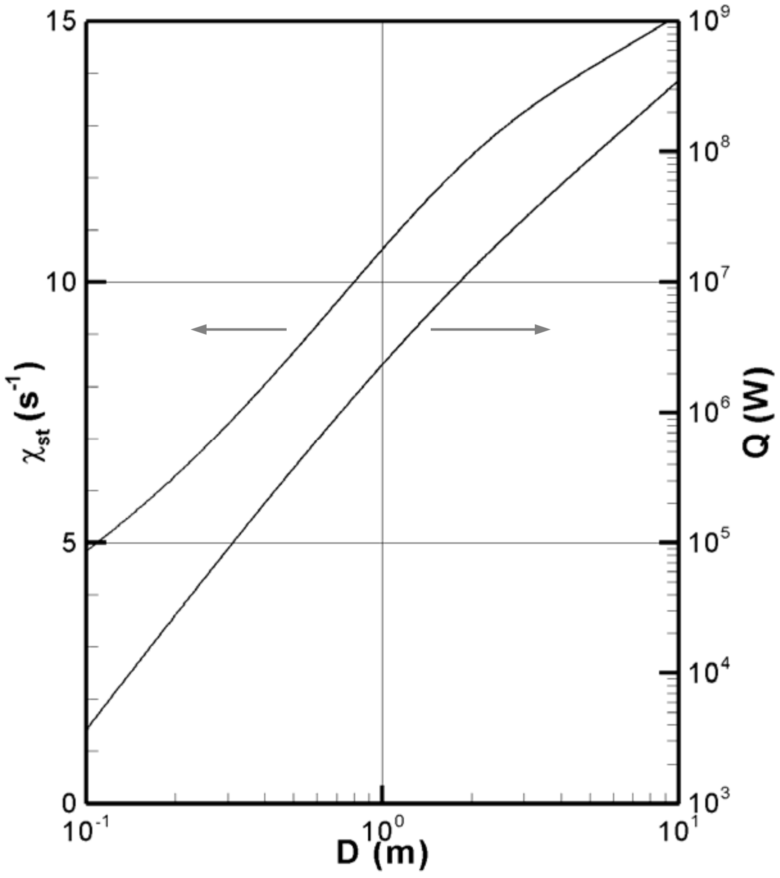
Kinematic Scales in Fires



Heptane Pool Fire

- Characteristic mean scalar dissipation rate at the flame tip as a function of pan Diameter (and Fuel specific parameters).
- Velocity predictions compare well with 1m diameter Methane flame measurements by (Tieszen, 2002).
- Another region of interest is the base of the flame where
  - Large scale laminar mixing dominates
  - We are examining the effect with direct numerical simulation

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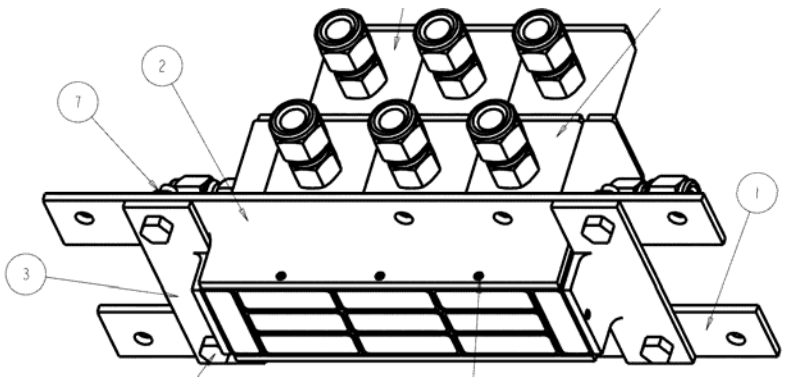
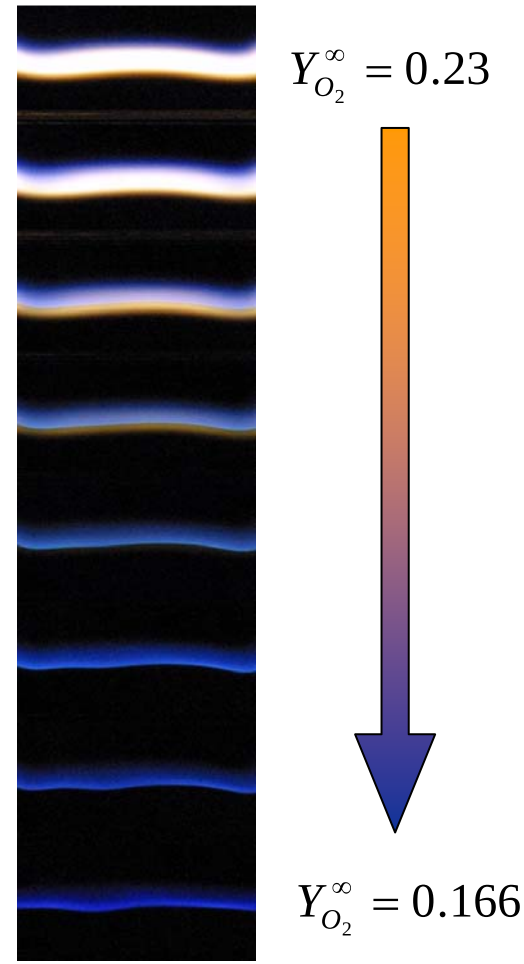
Experimental Approach



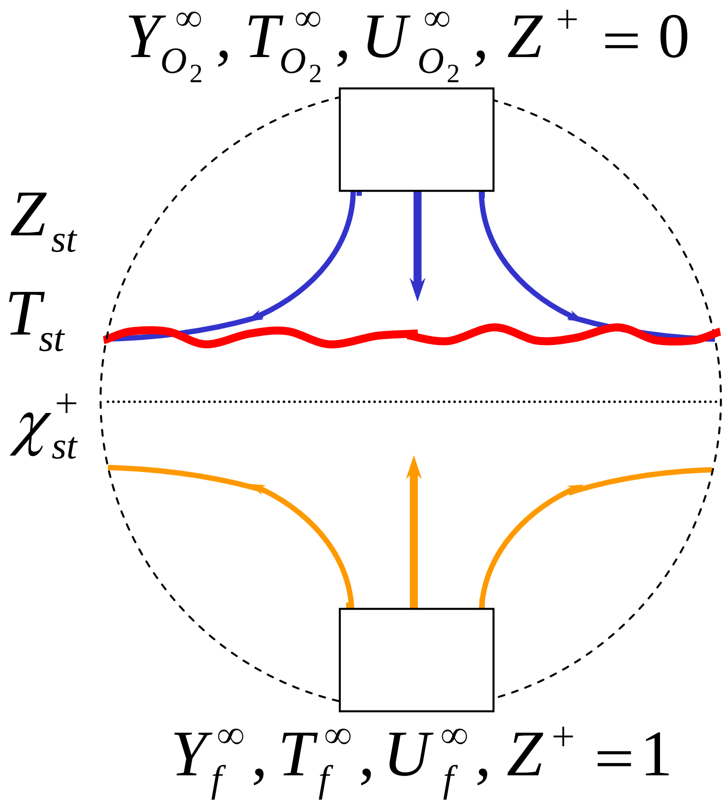
Burner Features

- Low strain flames: (12 s^{-1} – 75 s^{-1})
- Vitiated and heated reactant inlet.
  - 300 K < $T_{O2,\infty}$ < 600 K
  - 0.0 < $Y_{O2,\infty}$ < 0.23
  - 0.0 < $Y_{f,\infty}$ < 1.0
- Nitrogen co-flow flame isolation

$\chi_{st} = 0.49$ s^{-1}



OPPDIF Simulation Approach



$$\chi_{st} \equiv 2D_{th}(\nabla Z)^2 \mid Z = Z_{st}$$

- CHEMKIN 4.1 OPPDIF Solver
  - Steady state
  - GRI 3.0 Chemical Kinetics
  - Adiabatic (no radiation)
- Uses the von Karman similarity transformation to simplify the 3-D flame to 1-D equations.
- High resolution allows for exact determination of key parameters such as scalar dissipation rate and temperature at $Z = Z_{st}$.

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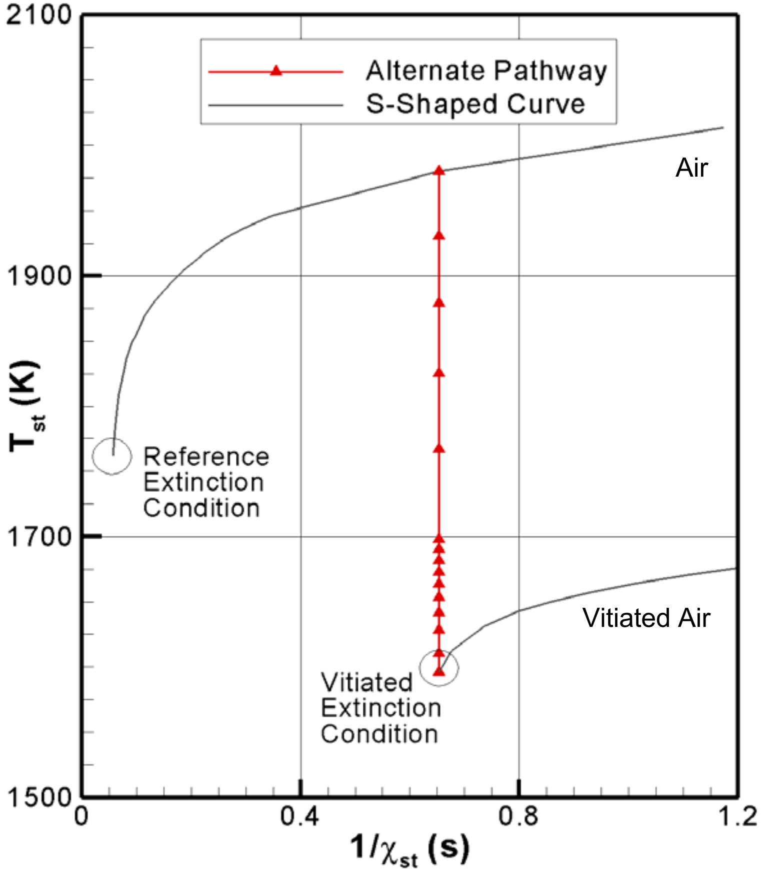
Extinction Criteria for Fires



Pathways to Extinction

Classical S-Shaped Curve
- Constant reactant properties
- Extinction by increasing strain

Alternative pathway
- Constant scalar dissipation rate
- Extinction by dilution of reactants
- Variable temperature reactants are also examined

Comparing extinction conditions
- Flame temperature
- Scalar dissipation rate

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Critical Scalar Dissipation Rate Models

Asymptotic Theory	*Da* Argument in Study
(Williams, 1975); (Peters, 1983); (Puri and Seshadri, 1986)	$Da_{crit} = \dfrac{t_{mix}}{t_{chem}} \approx \dfrac{\chi_{st}^{-1}}{A\exp\left(\dfrac{T_a}{T_{st}}\right)}$
Conventional: $\chi_{st} = \left(a_g/\pi\right)\exp\left\{-2\left[\mathrm{erfc}^{-1}(2Z_{st})\right]^2\right\}$	Corrected: $\chi_{st} = \varphi\left(Z_f - Z_{O_2}\right)^2 \left(a_g/\pi\right)\exp\left\{-2\left[\mathrm{erfc}^{-1}(2Z_{st})\right]^2\right\}$
$\ln\left(\dfrac{f(Z_{st})\chi_{st}}{T_{st,BS}^{5}}\right) = -\dfrac{T_a}{T_{st,BS}} + \ln K$	$\ln\chi_{st} = -\dfrac{T_a}{T_{st,BS}} + \ln\left(Da_{crit}^{-1}A^{-1}\right)$

$$T_{st,BS} = T_{O_2}^{\infty} Z_{st} + T_f^{\infty}\left(1 - Z_{st}\right) + \frac{\Delta h_c}{C_p} Y_f^{\infty} Z_{st}$$

Critical Scalar Dissipation Rate Models

Asymptotic Theory	***Da* Argument in Study**
Model 1	Model 2

Model 1:

$$\frac{\chi_{st}}{\chi_{st}^{ref}} = \frac{f(Z_{st}^{ref})}{f(Z_{st})}\left(\frac{T_{st,BS}}{T_{st,BS}^{ref}}\right)^5 \exp\left[-T_a\left(\frac{1}{T_{st,BS}} - \frac{1}{T_{st,BS}^{ref}}\right)\right]$$

Model 2:

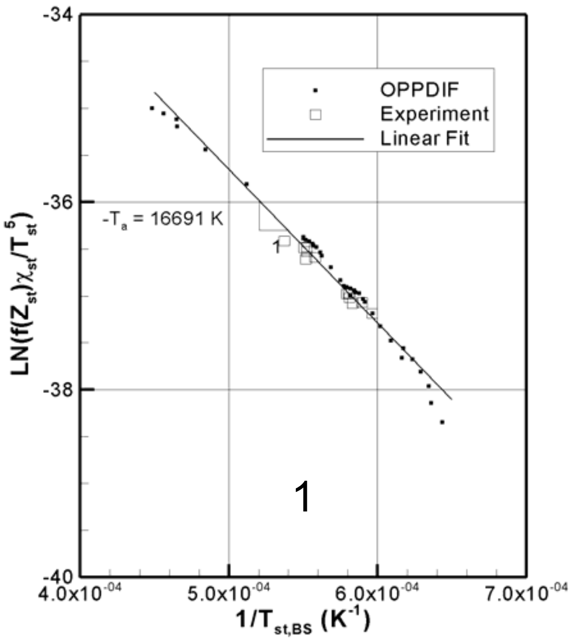
$$\frac{\chi_{st}}{\chi_{st}^{ref}} = \exp\left[-T_a\left(\frac{1}{T_{st,BS}} - \frac{1}{T_{st,BS}^{ref}}\right)\right]$$

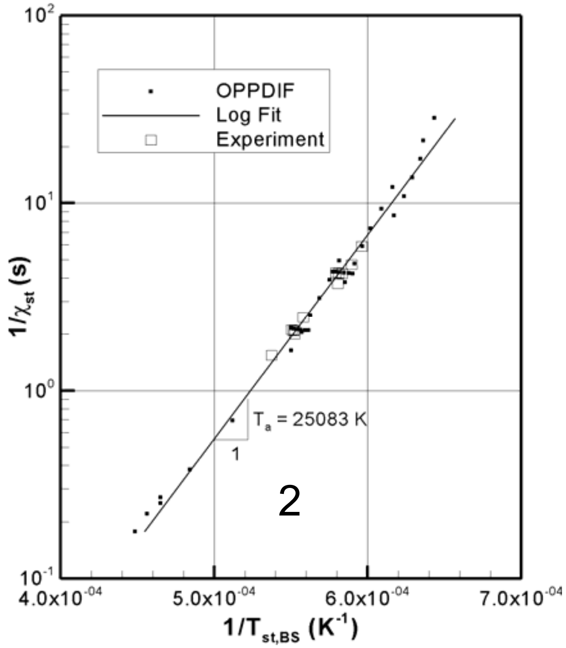
Model 1: $\chi_{st}^{ref} = 6.96\ \mathrm{s}^{-1}$

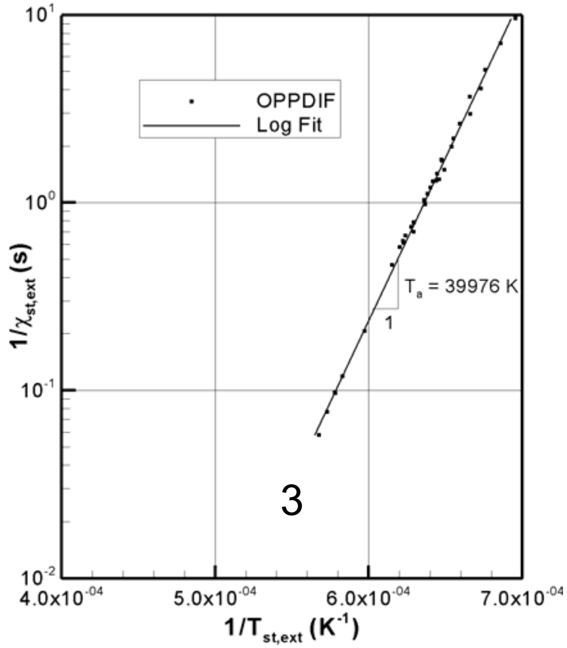
Model 2: $\chi_{st}^{ref} = 11.23\ \mathrm{s}^{-1}$

Normalization by a reference condition gives the model a convenient form

Determining Activation Temperatures







Model 1 – Asymptotic analysis following the method of Puri and Seshadri using Burke-Schumann temperatures and the original equation for scalar dissipation rate.

Model 2 – Critical Damköhler model using Burke-Schumann temperatures, and scalar dissipation rate from asymptotic analysis including density correction and renormalization.

Model 3 – Numerical observation of extinction behavior follows the critical Damköhler number behavior.

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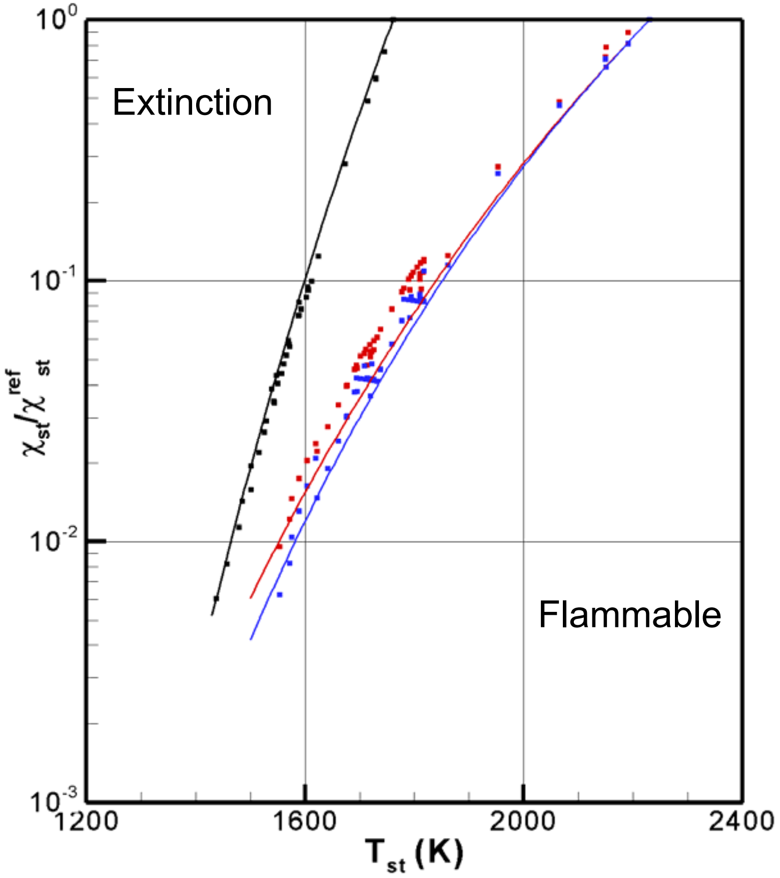
Critical Scalar Dissipation Rate Models



Extinction Models

Model 1 (Red):

- Data from Conventional χ_{st}
- Asymptotic analysis approach

Model 2 (Blue):

- Data from Corrected χ_{st}
- Critical Damköhler number approach
- Better agreement with χ_{st} and $\chi_{st} / \chi_{st}^{ref}$ from Model 3 due to added correction factors

Model 3 (Black):

- Data from definition of χ_{st}
- Critical Damköhler number approach

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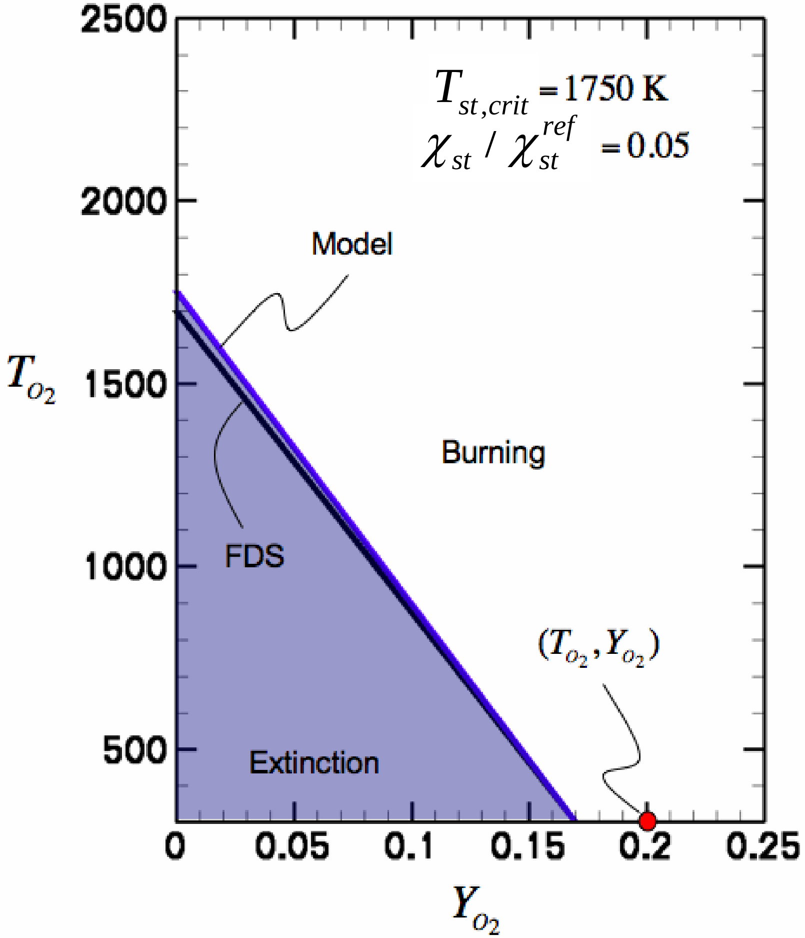
Extinction Map



Simple Extinction Map

- Extinction map created by specifying $T_{st,crit}$ or $\chi_{st} / \chi_{st}^{ref}$.
- FDS extinction map similar to current model at a low scalar dissipation rate (Model 2).
- Sample condition is vitiated, but still sufficient for burning.

Extinction Condition

$$Y_{O_2} < Y_{O_2,crit}$$

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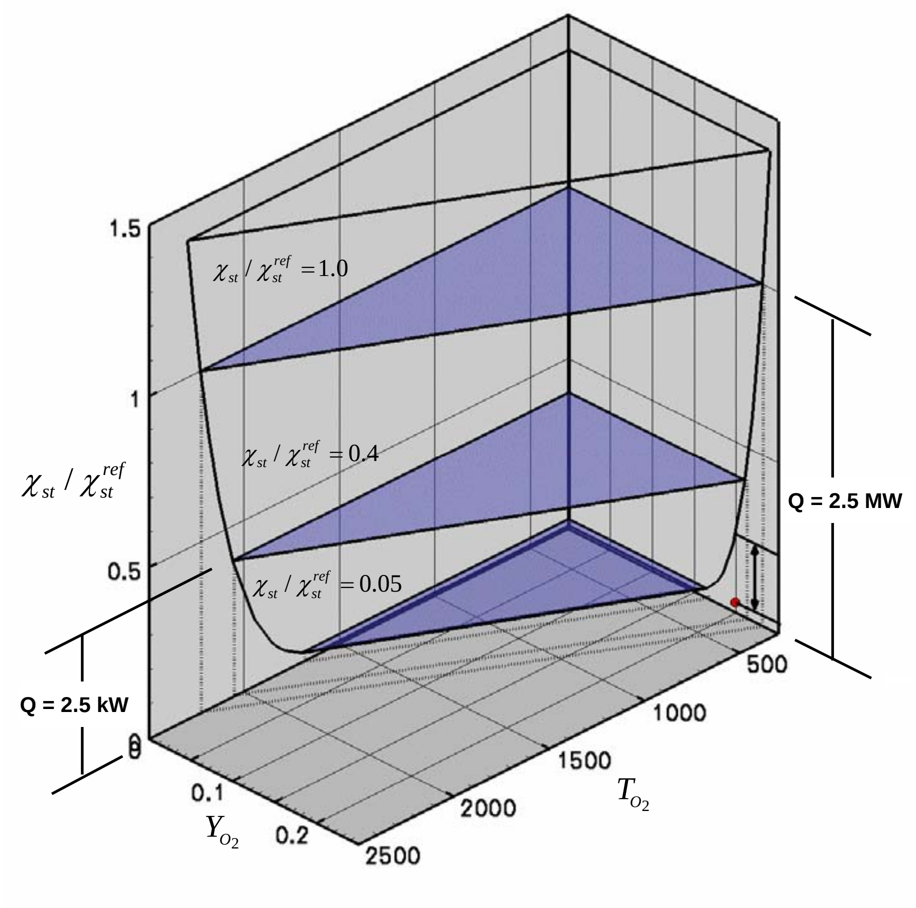
3D Extinction Map



3D Extinction Map

- Extinction region grows with increasing scalar dissipation rate.
- Fire size determines range of possible scalar dissipation rates.
- This view provides detailed physical insight, but adds complexity to extinction model

Extinction Condition

$$\chi_{st} / \chi_{st}^{ref} > (\chi_{st} / \chi_{st}^{ref})_{crit}$$

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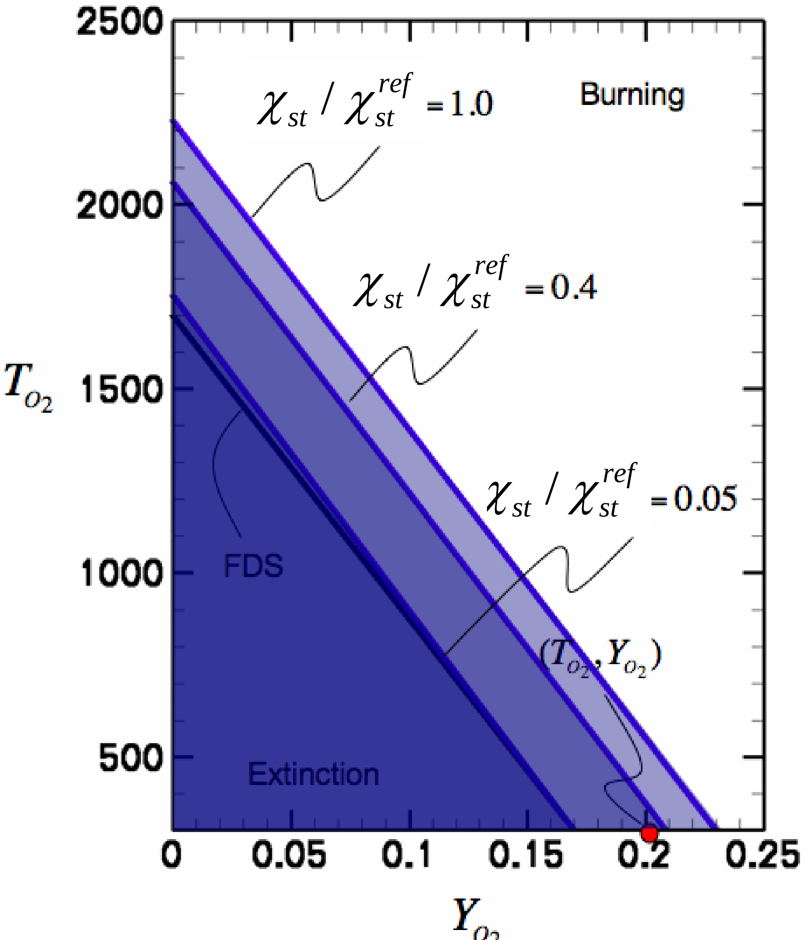
Extinction Boundary Analysis



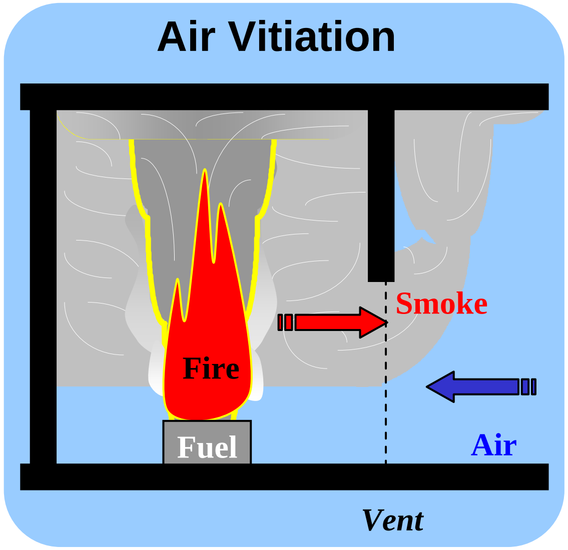
Projected 3D Extinction Map

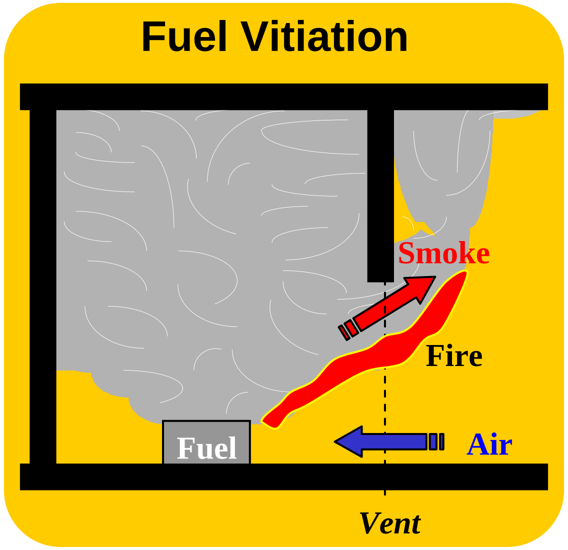
- 2D maps clearly reveal the effect of increased scalar dissipation rate.
- FDS map corresponds to a low and constant (one boundary) scalar dissipation rate assumption.
- Increasing fire size can expand the possible extinction conditions (flow dependent boundaries).
- The importance of **radiation losses** and **fuel vitiation** will be explored to determine if flow effects can be neglected.

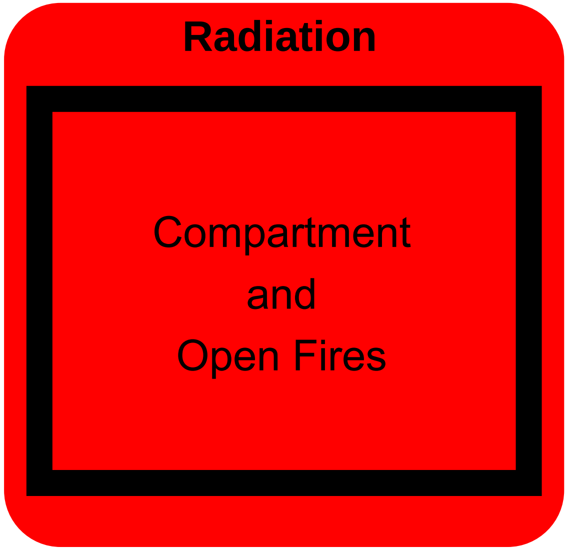
Summary of Current Work

- Developed an approach to characterize vitiated extinction in fires.
- Scaling argument indicates potentially significant scalar dissipation rates in large fires. (1m)
- Examined the application of three scalar dissipation rate extinction models considering Oxidizer vitiation.
- These models capture the essential physics of extinction but add unwanted complexity.
- The importance of **radiation losses** and **fuel vitiation** will be explored to determine if flow effects can be neglected.

Future Work







Burke-Schumann Critical Temperature Extinction Model

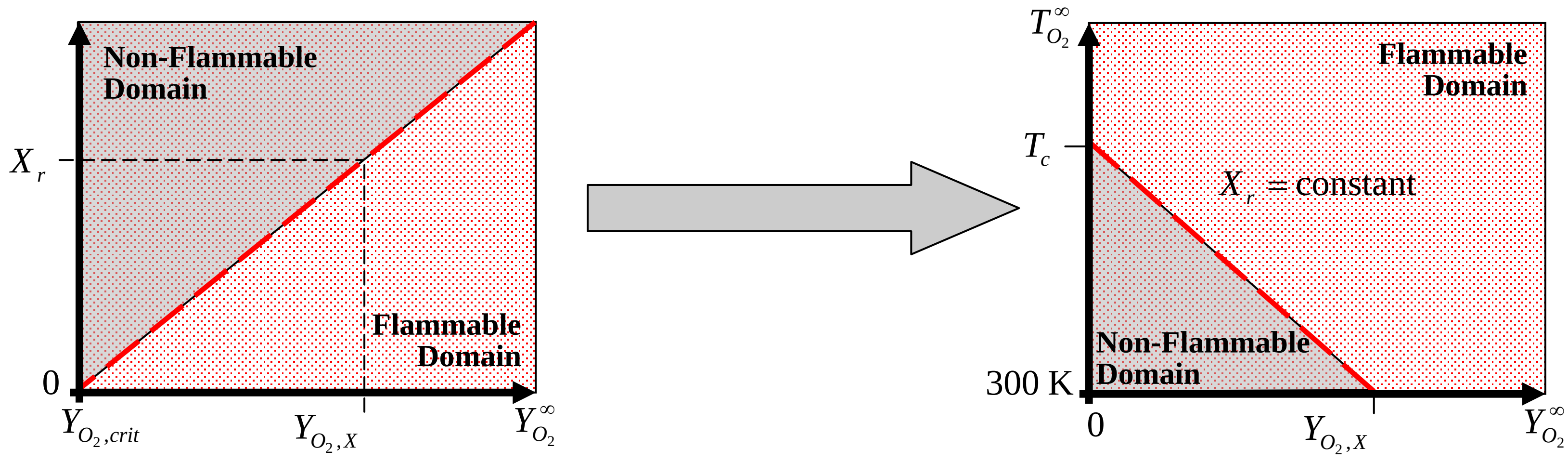
$$\left(T_{st}-T_c\right)=T_{O_2}^{\infty}Z_{st}+T_f^{\infty}\left(1-Z_{st}\right)+Y_f^{\infty}\left(\frac{Z_{st}}{Z_{st}^{0}}\right)\left(1-X_r\right)\left(T_{st}^{0}-T_u\right)-T_c$$

Extinction at $\left(T_{st}-T_c\right)\leq 0$

Future Work

Development

- Modify the extinction model to include fuel vitiation and radiation effects.
- Perform opposed flow experiments with imposed radiation losses and fuel vitiation to support model development.
- 2-D extinction maps can be derived from these variables in order to represent them in a similar way to the air vitiation case.
- Example for Radiation effects below:



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Future Work

Validation

- Simulate Pool Fires (Hamins, 1993-1996) and Reduced-Scale Enclosure (RSE) Experiments performed by NIST.

- Evaluate the critical temperature model's ability to reproduce combustion efficiency to determine if neglecting flow effects is appropriate.

Thank You